The Psychophysical Perception of the Key Odorants in Potato Chips

A Thesis

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Master of Science

by

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ABSTRACT

This research used sniff olfactometry (SO) to recreate the odor image of a potato chip from the olfactory responses to its most potent odorants. The thresholds for the key odorants (KO's), methanethiol, 2-ethyl-3, 5-dimethylpyrazine, and methional, were determined for each of four subjects, along with their responses to the KO's in mixtures. In binary mixtures, the equal odds ratios (EOR's) defined as the ratio of the concentrations of two of the odorants in a mixtures at which they were detected at equal frequency was determined along with the tertiary odds ratios (TOR's) defined as the ratio of the three odorants at which all three components were detected at equal frequency in tertiary mixtures. The configural odds ratios (COR's) were determined from the tertiary solution of the KO's that subjects identified as most like potato chips. The results found large variation in thresholds, EOR's, and TOR's, but remarkable similarity in COR's indicating that the potato chip odor image is derived from the same KO composition for different subjects even though they are not having the same sensory sensation.

BIOGRAPHICAL SKETCH

Madeleine was born and raised in Hunterdon County, New Jersey. She grew up on a farm, riding horses, bailing hay, and catching frogs with her sister. Her upbringing as a “lane girl” granted her the work ethic and agricultural interest that ultimately led to this thesis.

She attended the University of Delaware from 2011 to 2015, majoring in Food Science and minoring in Chemistry. While at the University of Delaware she was a blue hen ambassador, an agricultural ambassador, and played on many intramural sports teams. Madeleine plans to remain a blue hen for life.

During her undergraduate studies, Madeleine had two summer internships. The first was doing freeze thaw formulation and optimization in alfredo sauce, gravy, and tomato soup at TIC Gums. The second was a technical service internship at Ingredion Incorporated which she spent formulating eggless, clean label mayonnaise.

In the fall of 2015, Madeleine began her Master’s studies at Cornell. During this time, she acted as Teacher’s Assistant for four classes, Chef’s Chemistry, Wines and Vines, Grapes to Wine, and Winemaking Theory and Practice. Her work as a TA for the viticulture and enology classes strengthened her existing love of wine. Also during her Master’s studies, Madeleine adopted her dog, Potato, whom has been her tireless companion and comfort throughout even the most stressful times.

With the knowledge she has acquired under the guidance of her advisor, Terry Acree, Madeleine feels ready and is excited to enter the food industry upon the completion of this degree.

Dedicated to my family:
To my amazing parents, Susan and Phil, for the lifetime of support, encouragement, advice, and love.
To my big sister, Bunny, who also happens to be my best friend.

How would I have ever made it here without the three of you?

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Potato- my dog, my friend, my good girl.

An especially big thank you to my subjects who took time out of their busy lives to smell stinky compounds for me.

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LIST OF ABBREVIATIONS

SO – Sniff Olfactometry

KO – Key Odorants

EOR – Equal Odds Ratio

TOR – Tertiary Odds Ratio

COR – Configural Odds Ratio

GCO – Gas Chromatography Olfactometry

PFA - Perfluoroalkozy

AFC – Alternative Forced Choice

OE- Olfactory Epithelium

OR- Olfactory Receptor

ORN – Olfactory Receptor Neuron

OB- Olfactory Bulb

JND – Just Noticeable Difference

MAL- Methional

MOL- Methanethiol

2E3,5DP- 2-ethyl-3,5-dimethylpyrazine

EtOH- Ethanol

Let us dive now into the aromatic world of the potato chip.

CHAPTER 1: Published Paper

Computing Odor Images

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Abstract

Beginning with results of Laing (1986), many mixture studies indicate that as little as 3 odorants in a complex mixture are involved in the perception of an odor image(Laing and Francis 1989). Examining published data on food odors, it was shown that less than 250 odorants contribute to the aroma of all foods(Dunkel, Steinhaus et al. 2014). This would imply that it is the ratio of a small number of key odorants (KO) that create food odor images and Laing's result may be direct evidence of the simplicity of the computational process(Cleland 2010). This perspective examines psychophysical methods that may reveal the algorithms that encode odor images.

Keywords: sniff olfactometry, odor image, odorant mixtures, Laing limit, olfactory white

Introduction

Multitudes of odorants surround us every day. From fresh cut grass to a pot of hot coffee, the odors we encounter in our daily routines can capture out attention, modify our memories, and shape our experiences. But while that coffee aroma will fill a room and the smell of fresh cut grass brings you back to your childhood, it is generally accepted that there are hundreds of odorants working behind the scenes, subliminal, but still activating our olfactory receptors. However, 35 years ago, David Laing and coworkers(Laing and Francis 1989) has challenged this assumption in psychophysical experiments by showing that humans have an extremely low capacity to identify odorants in mixtures(Jinks and Laing 1999, Jinks and Laing 1999, Laska and Teubner 1999, Marshall, Laing et al. 2006). The frequency at which subjects could identify correctly both odorants in a binary mixture was less than 35% and the ability to identify all three odorants in a tertiary mixture was less than 14%(Laing and Francis 1989). This is an example of one of the three levels of analysis David Marr described for the study of visual perception: computational = what the system does, algorithmic = rules that applies to the input during computation to yield an output, implementation = the biology that does the work (the "wetware")(Cleland 2010). In olfaction the 3 odor limit to the analysis of mixtures is a computational limit imposed by some algorithm that causes us to ignore most other components even though they are above their threshold and are surely activating receptors. Somewhere in the neuroanatomy are cellular implementations and neuronal connections housing the algorithms that produced this computational result(Marr 2010),(Cleland 2010). However, the reproducibility of psychophysical experiments indicate that a robust encoding – decoding process must operate(Kurtz 2012),(Chapuis and Wilson 2012).

The challenge for flavor scientists is to use psychophysical experiments to provide insight into the computational behavior of a sensing organism and to locate the algorithms that underlie them. They must obtain results that can be compared with data from other models using the same experimental standards and parameters. Only then can we make inferences from parallel experiments with non-human models. One of the ways to accomplish this is to design human psychophysical experiments that parallel experimental standards used with other models. In this perspective we discuss an application of olfactometry to the computational level of odor image analysis(Cleland 2010).

Recognizable odorants in mixtures.

The 1989 paper of Laing & Francis(Laing and Francis 1989) redefined the study of olfaction; by analyzing odorants in mixtures, they were able to determine that there is a finite number of odorants that can be recognized in a mixture. Beyond this limiting number there is a sharp drop in the perceptibility and ability to identify additional odorants accurately and the ability to correctly identify all components of a mixture was insignificant using mixtures of just five odorants(Laing and Francis 1989). In the years since, the belief that there is a 3-odorant limit to odor analysis of mixtures during a single puff has slowly gained acceptance(Thomas-Danguin, Sinding et al. 2014). Additionally, studies conducted on the effect of training and expertise on this limit indicate that there is little to no effect on the recognizable odorant limit, even after training, or when the subjects are trained perfumers(Livermore and Laing 1998),(Rinberg and Gelperin 2006). An obvious question is whether the

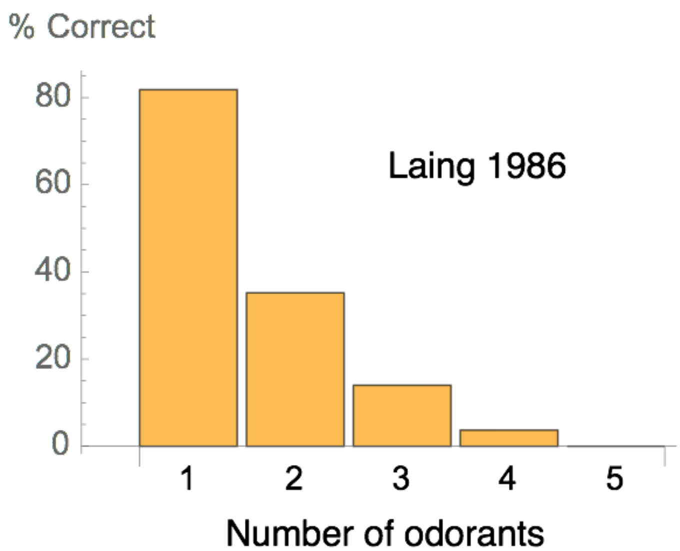

Figure 1. Bar plot of the data from ref 1 showing the ability of a person to identify odorants in a mixture as a function of the number of odorants in the mixture.

types of odorants had an effect on this limit. While as a rule, the type of odorants used in these studies did not change the number of odorants detected, familiarity with the odorants did increase identification accuracy, indicating that memory as well as odorant concentration contributes to the rapid identification of odorants in mixtures (Laing and Francis 1989). This remains true even when the odor is merely misidentified as something familiar. In multiple studies summarized in Wilson and Stevenson's "Learning to Smell," the relationship between familiarity and perceived intensity of an odor are directly correlated(Wilson and Stevenson 2006). While this limited ability to recognize more than a few odorants in a mixture may seem like a weakness, Laing suggested that, "the apparent inability may in fact reflect a highly efficient neural encoding mechanism which facilitates the rapid discrimination and identification of multicomponent object odors in the environment." (Livermore and Laing 1998),(Resulaj and Rinberg 2015).

The limit of recognizable odorants indicates that any real life complex odor mixture can be recreated with just a few odorants. In a study of a mixture of three odorants with seemingly unrelated odors in a mixture they smelled like pineapple to humans while none of the individual components had a pineapple smell on their own(Le Berre, Beno et al.

2008, Le Berre, Thomas-Danguin et al. 2008). Similar results were obtained with newborn rabbits using the same three compounds (Coureaud, Thomas-Danguin et al. 2008, Coureaud, Gibaud et al. 2011, Barkat, Le Berre et al. 2012). Laing and Francis also address the idea that the combination of just a small number of odorants can produce a new odor, unlike any of individual components(Laing and Francis 1989). This idea that complex odors can be recreated with three or four components is integral in the future of the study of olfaction and of enormous practical importance to the flavor industry. Figure 1 shows a graph of data from Laing's 1989 paper in which subjects trained to identify 5 odorants accurately ($P > 0.8$) could only identify all the odorants in a 3 component mixture of the 5 with accuracy. The persistent question remaining is how such a 3-odorant limit comes into play with the discriminatory skills of a sommelier to identify wine, the ability of many animals to use odorant mixtures to understand their worlds, and the models of olfactory processing emerging from neurobiology(Cleland 2010). More simply, how does an organism decode odor mixtures? How do they use salient and subliminal information extracted from a whiff to stimulate perception and behavior. The answer must explain the phenomena of the "Laing limit of 3" as well as the simultaneous suppression of odorants in mixtures and their adaptation in sequential presentations.

Suppression and Adaptation

It is likely that the limit on the number of recognizable odorants in mixtures is due to the interaction between odorant signals in the network of neurons that process odorants into odors. Suppression and adaptation are among the chief modulating effects observed many times in the study of mixture perception, and these effects indicate that odorants interact with each other in different ways. Laing and Wilcox examined this phenomenon in binary mixtures. They observed that, while characteristics of both components in a mixture remained detectable, certain features of each component was suppressed with the addition of other odorants(Laing and Willcox 1983). Notably, the suppression and adaptation in odor mixtures can be somewhat predicted from the similarities and differences in odorant qualities.. For example, Kurtz et al. showed that the "citrus" smelling odorants structurally similar C8, C10, C11 n - aldehydes, cross-adapted each other but did not adapt to the green smelling but structurally similar n - C6 aldehyde, hexanal (Kurtz, Lawless et al. 2010). Furthermore, the 3 similar smelling "citrusy" aldehydes do not suppress each other in mixtures while they do suppress hexanal and vice versa (Kurtz, Barnard et al. 2011). It is not surprising that the rI7 receptor, first de-orphanized in 1998, has all the citrus smelling odorants in its receptive field while hexanal is not (Zhang and Firestein 2002). Kurtz further examined interaction of C6, C8, and C10 aldehydes in binary mixtures. Here, the similar smelling C8 and C10 aldehydes cross-adapt but the dissimilar smelling aldehydes, C6 and C8, suppressed each other when mixed. It seems that odorants cross-adapt when they smell alike and suppress each other when they don't because of their odor dissimilarity, not because of their structural similarity(Kurtz, Barnard et al. 2011). At the very least this implies that the processes that regulate suppression are somewhat different from those that govern adaptation. In other studies of binary odorant mixtures the overall intensity was less than the sum of the intensities of the odorants individually, but always stronger than the mean intensities of the individual odorants and follow a vector model(Berglund and Olsson 1993),(Berglund and Olsson 1993).

Non-human models also show non-additive effects of odorants in mixtures, for example, rats are instinctively attracted to or repelled by specific odors for safety and reproductive purposes. However, when these attractive and aversive odorants are combined in mixtures, the rats respond to the attractive odorant, indicating that the attractive odorant is suppressing the aversive odorant (Saraiva, Kondoh et al. 2016). The effect of suppression and adaptation can also be seen in olfactory studies related to time. In both humans and non-human models it has been shown that when faced with mixtures of similar smelling odorants, subjects tend to take longer to identify the individual odorants present in the mixture. Perhaps suppression is occurring in mixtures of similar odorants, making the analytical process of identifying odorants more difficult(Wise, Olsson et al. 2000).

Mixture perception

As an even more striking phenomenon, and in addition to a limit of 3 or 4 detectable odorants in a mixture, humans seem to be unable to detect a single component in a mixture of 16 different odorants when they are at the same odor intensity(Jinks and Laing 1999). This phenomenon was more dramatically demonstrated when a mixture of 60 different odorants was prepared at concentrations of similar odor intensities. This mixture had a weak nondescript odor the researchers dubbed “Lorax”. None of the component odorants could be recognized in the mixture but there was a faint nondescript smell. Furthermore, when the mix of 60 was subdivided into 2 random mixtures of 30 components they both smelled “Lorax” (Weiss, Snitz et al. 2012)! It seems that the algorithm humans use to process signals from complex mixtures of odorants requires that a small subset of the components be present at an odor potency some what larger than the remainder of the constituents. Examining the gas chromatography-olfactometry (GCO) data published in the last 30 years show the same pattern in natural products. A few Key Odorants (KO) dominate natural product GCO data as demonstrated in the publications (~ 900) that make up the Flavornet(Acree 1997). Furthermore, an analysis of 119 publications that fit rigorous criteria for odor activity involving 220 foods, Andreas Dunkel and his colleagues could find only 230 unique odorants(Dunkel, Steinhaus et al. 2014). Taken 4 at a time that would mean there are over 113,000,000 possible distinguishable odorant patterns from a combination of any 4 of these 230 food odors – more than enough patterns to encode ecologically important features of any organism's olfactory space. And this does not even include the number of patterns that can be created with different *levels* of the 4 odorants.

Therefore, a small number of stimulants may be all that is needed to encode complex images and the "Laing effect" may be direct evidence of the simplifying of algorithms involved in computational processing. To the extent that the encoding process is similar in rats and humans, maps of the neural projections from the glomerulus to the anterior piriform cortex indicate that connections between these two bodies are unique but not ordered in any simple way, e.g. the map in the main olfactory bulb is not a major feature of the "cortical response mosaic". However, reproducible psychophysical behavior indicates that a robust encoding – decoding process must be in operation(Chapuis and Wilson 2012, Kurtz 2012). The challenge then is to determine how humans process relatively simple mixtures of odorants first into a simple input code and then into more complex output: a multitude of unique odor objects representing our olfactory space.

Sniff Olfactometry

Most research on odor mixture perception in humans has relied on the correlation of psychophysical and sensory measurements of intensity with measures of odorant concentration. These methods tend to generate data on individuals very slowly. As pointed out by Wilson & Stevenson(Wilson and Stevenson 2006) "[There is a]... need to develop new approaches to

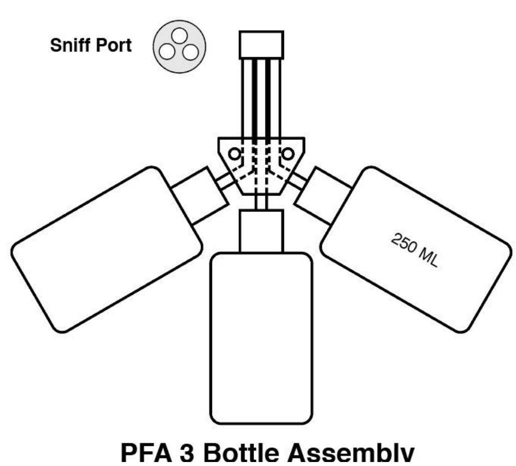

Figure 2. Three-bottle assembly used in the SO to deliver up to three puffs in a trial singly, sequentially, or simultaneously.

testing olfactory discrimination that enhance both the sensitivity and speed… [Most sensory tests]...are very time consuming and yield relatively little data per participant. Techniques such as those pioneered by Rabin and Cain(Rabin and Cain 1984), which involve the identification of a target odor in a mixture are the sort of thing we have in mind.” Sniff olfactometry (SO) was developed to address these questions.

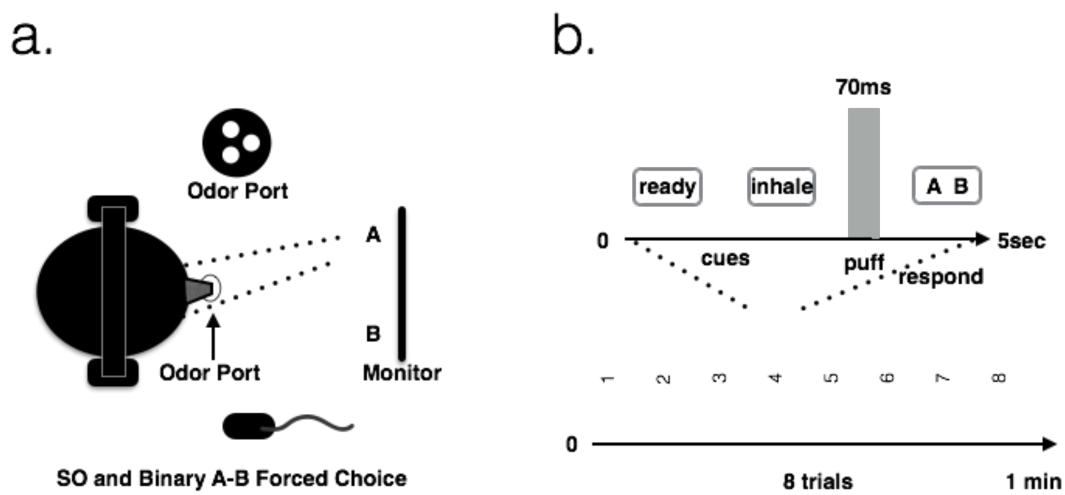

Figure 3. (a) Experimental arrangement of the SO is shown along with a view of the odor port from above; (b) time line for single probability measure.

In order to improve the study of odor images in humans stimulated by simple mixtures of key odorants we used an olfactometer to deliver defined compositions with minimal stimulus exposure to <100ms, trial duration to <5sec, and subject adaptation(Wyckoff and Acree 2016),(Acree, Roche et al. 2015),(Acree, Kurtz et al. 2014),(Acree and Kurtz 2013),(Kurtz 2013),(Kurtz 2012). Using odorants found in commercial potato chips (crisps, for the British reader) we have studied the binary interaction of key odorants and demonstrated diverse but reproducible response. Estimating the chemistry that creates an odor image of potato chips, we used three key odorants (i.e., methanethiol, methional, 2-ethyl-3,5-dimethylpyrazine) to create the compositions of the three odorants that yield a 'potato chip' image (as opposed to the images of the individual components smelling rotten cabbage, potato, and toast) (Acree, Kurtz et al. 2014),(Acree, Roche et al. 2015). In summary, the results indicate that the interactions are very specific to the sensation and range from additive to intensely suppressive. Whether these interactions are determined by the structure of cortical activation more than by chemical features of the odorants is a compelling question for both flavor scientists and neurobiologists.

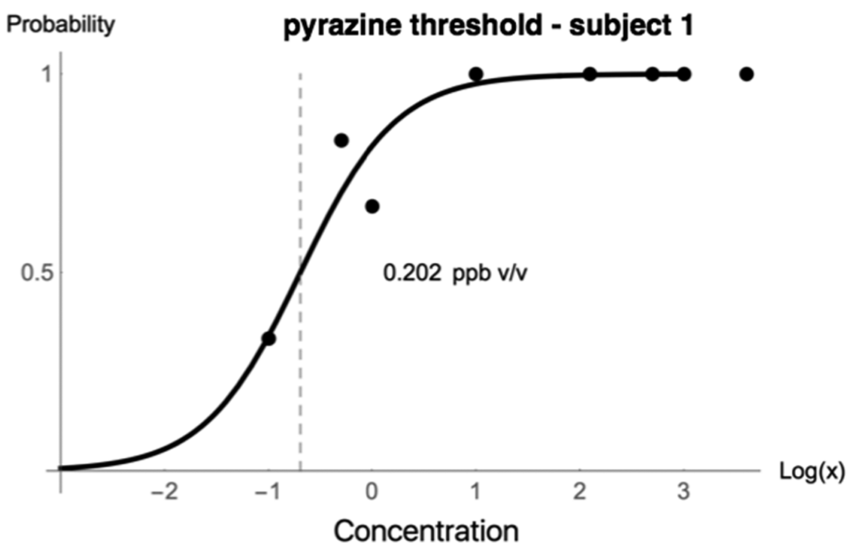

Figure 4. Plot of the probability of correctly recognizing an odorant as a function of concentration. The curve is a logit model fit to the data. Here the threshold is defined as 50% probability. It could easily be defined as 75%.

The design criteria for the SO were based on 250 ml PFA squeeze bottles(Wyckoff and Acree 2016). The PFA exhibits low odorant scalping, can contain a model bolus to represent retro nasal smell, a headspace designed to deliver any odorant concentration in air released from model mixtures, or material representing many different ecological odorant sources: foods, beverages, ingredients, etc. The PFA bottles are easily managed when pre-installed in a 3-bottle assembly that maximizes sample exchanges (<5 sec.), with puffs delivered along a 10 cm path minimizing contamination, and allowing 1 to 3 bottle protocols, i.e. single puff assessments, 2AFC, 3AFC, sequential or simultaneous stimulations, shown here in Figure 2. The SO can, using high-speed actuators (9 cm/second), expel ~15 ml headspace puffed from a sniff port with rise and fall times less than 5ms and a puff duration of 70ms. Controlled by the computer program, PsychoPy™ (Jonathan Peirce)(Peirce 2007) the timing of the puffs, presentation of auditory and visual cues can be delivered double blind, randomized, and recorded automatically. Thus, a single trial can be less than 5 sec.: much briefer than most human sensory techniques. To date, the results indicate that the interactions are very specific to the sensation and range from additive to intensely suppressive.

Potato Chip Odor Image

Potato chips are a simple model for the study of odor image formation simply because only 3 KOs, methional, methanethiol, and 2-ethyl-3,5-dimethylpyrazine, are present at 10 times the potency of all the other odorants in the headspace above a simulated bolus containing water and crushed chips. These components smell like "potato", "rotten cabbage", and "toast" respectively and are not easily confusable with chips (Acree, Roche et al. 2015). Unlike most other foods, potato chips have 3 key odorants that are within the 3 - odorant recognition limit proposed by Laing. Diagramed in Figure 3a is the experimental arrangement for using the SO to determine thresholds for each of the potato chip KOs.

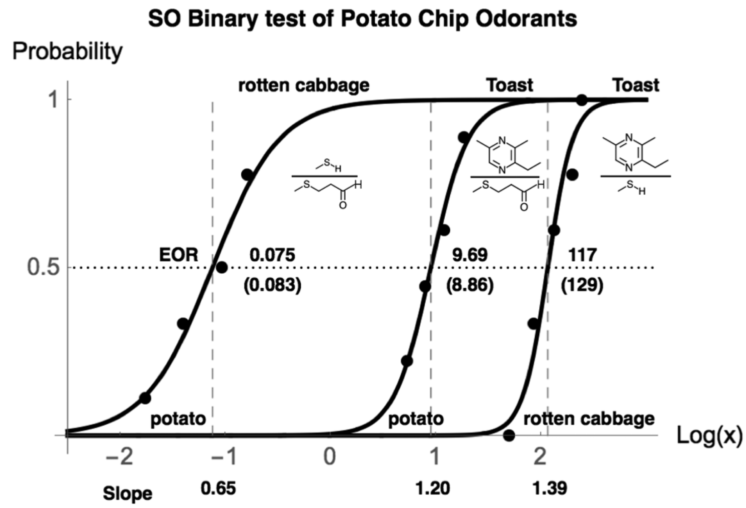

Figure 5. Comparison of the binary probability plots for each pair of potato chip KOs. The difference in slope of each curve indicates vastly different binary interaction.

The subject is shown from above the odor port wearing noise-canceling headphones, a mouse used for input, a monitor used to observe queries and cues, and a diagram of the odor port configuration. Figure 3b shows the time sequence for a single trial in which a subject is asked to choose between descriptors, objects, or signs used to train the subjects for a 2AFC recognition task.

After the subjects were trained with an association task, their threshold was determined for each KO in a binary forced choice between ethanol-water blank and solutions of each odorant in ethanol-water at different concentrations. Figure 4 shows the logistic curve fit to the proportion a sample was associated with "toast" during 8 replications plotted against the log of the concentration of 2-ethyl-3, 5-dimethylpyrazine solutions in the bottle. Threshold is estimated as the concentration at which the logistic plot intersects 0.50 probability, in this case 0.202ppb or (0.647 if the threshold criteria is 0.75). The threshold for methional was 4.2ppb and for methanethiol was 92.1ppb. From these values an estimate of the equal odds ratio (EOR) or the ratio of the concentrations of a binary mixture of 2 KOs that yields equal probability of detecting either component. Starting with an EOR estimate of 5 times the threshold of each of the binary components, an iterative change in the ratios will yield a logistic probability plot over concentration ratios at probabilities from 0 to 1.0. The ratio of 0.5 is defined as the EOR for that pair of odorants.

Figure 6 shows the binary probability plots for each pair of potato chip KOs. The EORs for each pair of odorants are shown at the inflection point of each curve and the predicted EORs from the other binary pairs are shown below in brackets.

The predicted values are very close to the measured values, indicating predictability between pairwise interactions. However, their slopes are quite different indicating that at least 1 ratio will deviate significantly from the other two. From the three binary plots, we can estimate a tertiary odds ratio (TOR), the concentrations at which all three components would be detected equally.

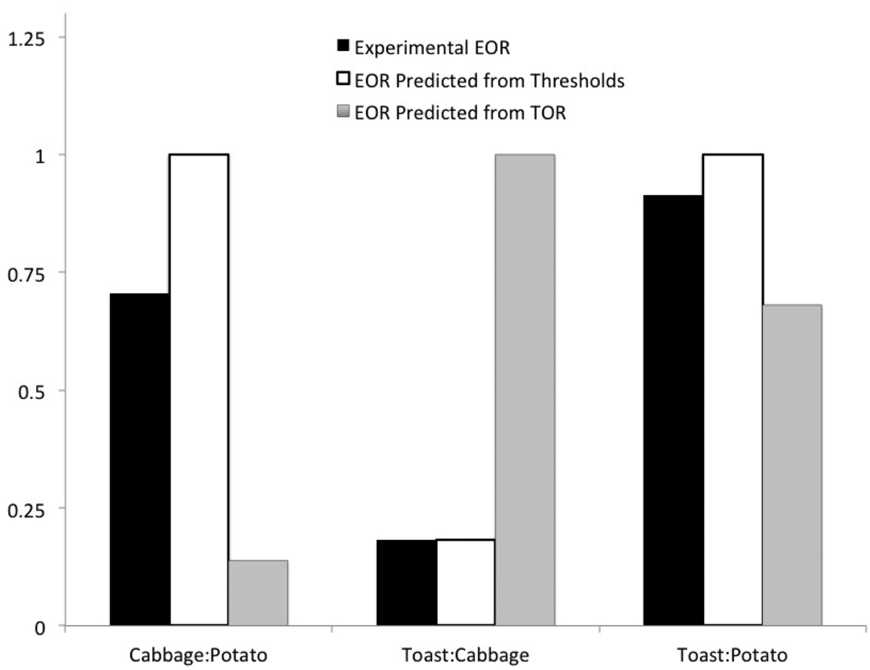

Figure 6. Comparisons of equal odds ratios for each pair of compounds found experimentally (left), as predicted from thresholds (center) and from tertiary odds ratio (right). The addition of a third component to a binary mixture reduces the predictability of the binary EORs.

Preparing a mixture of all three components and adjusting them until each component in the mixture was detected 33% of the time. Figure 7 shows the binary EORs predicted from the thresholds (white bars), measured directly from the binary mixtures (black bars), and calculated from their concentrations in the tertiary mixture (grey bars). For one subject at least, the addition of just one component to a binary mixture had a marked effect on the perception of the others. If we define a Configural Odds Ratio (COR) as the ratio at which a mixture of potato, toast, and rotten cabbage smells like potato chips then we can compare the TORs for different subject with their CORs and look for algorithms that may explain their perceptions. To the extent that subjects respond differently to odorants singly and in mixtures they will show different responses in the sniff olfactometer but they may have the same COR for potato chips since that would be defined by the odorant ratios in the chips. Presumably, they have made an association between the same potato chip object and their different odorant experiences. his is one of the questions compelling us to us the SO a Sniff Olfactometry to investigate odor image formation.

This perspective began with the general acceptance of the Laing Limit (humans have great difficulty recognizing all the odorants in mixtures greater than 3) and the observation that humans cannot recognize a single *odorant in mixtures with 16 – 60 odorants at equal potency. This limits the receptive field for odorants in mixtures or their perception as an odor image associated with the mixture or with a small number odorants, the Key Odorants. There may not be a strict limit on the size of the receptive field but instead threshold below which odorants are not recognizable. Instead, a few may be required for the formulation of an odor image. TDN in Riesling wine(Acree and Kurtz 2013), iso-butyl-2-methoxypyrazine in Sauvignon Blanc wine (Acree, Roche et al. 2015), and cis-roseoxide in Gewürztraminer wine(Ong and Acree 1999) are examples. It is possible that the computational and algorithmic processes that determine how elemental and configural processing is used by the brain cause the Laing limit and the Lorax effect. Nevertheless, it is clear that olfactory interpretation of odorant mixtures by the brain is fast, it involves an ad hoc generation Key Odorants(Acree and Arn 1997, Grosch 2001, Dunkel, Steinhaus et al. 2014) and can opt to see a single odorant or a mixture as either an element or a configuration i.e. an odor image (Livermore, Hutson et al. 1997, Kay, Crk et al. 2005, Sinding, Thomas-Danguin et al. 2011, Thomas-Danguin, Sinding et al. 2014) - a gestalt. When humans try to understand the smell of mixtures it is a similar to seeing the famous Duck-Rabbit ambiguous figure of Jastrow.(Jastrow 1899) Visual elements of the scene are instantly* *translated into the head of a duck or upon inspection a rabbit…and back again to a duck. It is possible that some parts of the computational processes are same for both vision and olfaction.*

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Chapter 2: The Psychophysical Perception of the Key Odorants in Potato Chips

1. Introduction

Would a potato chip by any other name taste as salty? What causes us to crave certain foods? What is it that makes our mouths water when we open a bag of potato chips, and reach for one more when the bag is empty. Just imagining a food, or its 'odor image', can evoke emotional and physical responses. These responses likely come from the chemicals found in the food as well as our psychological perception of the food. But are these responses the same for everyone? We all call a chip a chip, but when we are eating chips at a party, are we all experiencing the same chip?

We can begin to answer these questions by studying the psychophysical perception of the key odorants in a potato chip. In 1989, a study published by David Laing and G.W. Francis examined the ability of humans to detect odorants in a mixture. This was done by asking subjects to identify all odorants in mixtures of up to five odorants. The results found that the ability of subjects to correctly identify all of the odorants in a mixture was less that 4% in quaternary mixtures (Laing and Francis 1989). Other related studies have found that subjects are able to successfully identify odorants in mixtures of up to 8 odorants (Jinks and Laing 1999). Many additional studies have been performed that show that the ability to recognize odorants in mixtures does have a limit (Laska and Teubner 1999), (Marshal, Laing et al. 2006). This is especially apparent in the representation of olfactory white (Weiss, Snitz et al. 2012). Several factors have been examined to see if they change these results of the limit to identify odorants in mixtures, such as odor type (Livermore Laing 1996) and training (Livermore and Laing 1996), (Rinberg and Gelperin 2006), but the results remained unchanged. The only exception to this is with familiarity, as it has been shown that more familiar odorants are more easily identified in odor mixtures (Laing and Francis 1989), (Wilson and Stevenson 2006). Studies such as these indicate that there is a finite number of odorants that humans can identify in mixtures. This furthermore implicates that mixtures of odorants can be recreated using just a few of the most potent odorants in the mixture.

These studies on odor mixtures can be translated to food products, because the aromas we identify when smelling food are most simply mixtures of odorants. Potato chips, for example, have been analyzed using Gas Chromatography Olfactometry (GCO) (Acree, Roche et al. 2015). The results of the GCO show that there are three components in the aroma of potato chips that are significantly more potent than the other odorants present in potato chips. In fact, all but these three key odorants (KO) are present at less than 1% potency. Therefore, it stands to reason that the odor image of a potato chip may be recreated using only these three key odorants. The simplicity of the potato chip aroma is most made up by only 3 odorants, makes it an ideal model for the study by increasing the simplicity of the odor image recreation.

1.1 Olfactory Perception

Olfaction begins with the detection of small molecules (< 500 Daltons) dispersed in the air that passes over the olfactory epithelium (OE) in the roof of our nasal cavity by an olfactory receptor (OR) neuron (ORN) in the OE. The air reaches the OE from one of two routes, orthonasally, drawn in through the nose by the lungs, or retronasally, exhaled from the lungs through the nose or puffed into the airway by mouth manipulations. This study focuses only on the perception of odorants detected orthonasaly. The OE contains millions of ORs functionally segregated by 400 variants of a gene that encodes receptor protein in the transduction pathway of the ORN. When an odorant contacts an ORN, it is bound and activated by one of these ORs. The ORNs then send signals to the olfactory bulb (OB), located on the ventral surface of the frontal lobes. The bulb connects to the temporal lobe via neurons in the olfactory peduncle which contains the anterior olfactory nucleus. From the temporal expands the periform lobe, part of which contains the piriform cortex. The piriform cortex is the major component of the primary olfactory cortex and the first target of neurons originating in the OB. Beyond this complex olfactory system is the rest of the human brain where olfactory processing interacts with many cortical brain functions. It is here that olfactory sensations and perceptions modulate experience and behavior. This study investigates some effects of odorant composition on odor perception and what it infers about experience (Keller and Vosshall 2004).

1.1.1 Theories in Olfaction

When one begins to study olfaction, two principal theories quickly become apparent. The first is that when organisms experience a mixture of odorants, they experience each element within that mixture individually. This theory is commonly referred to as elemental perception of odorants. The second theory claims that when a mixture of odorants is perceived, no individual odorants are detected, but instead the organism experiences the mixture as a unique entity unlike any of its individual components. A study providing convincing support for elemental processing conducted on mice examined their responsiveness to two different odorants separately and in mixtures after being exposed to either one of the odorants or the mixture. The results showed that when a mouse had been exposed to a mixture of two odorants, their responsiveness to the two odorants individually increased, indicating that when they smell a binary mixture they are smelling both components of the mixture elementally making them more responsive to the individual components. Furthermore, the study showed an increase responsiveness to the mixture when the mice were trained to recognize and respond to the individual components of the mixture separately than when trained to recognize and respond to the mixture itself (Coureaud, Thomas-Danguin et al. 2014). In 2005, L. M. Kay conducted a study that supported the elemental theory. The study was done on mice, examining simple binary mixtures (Kay, Crk et al. 2005). A study that appeared to support the configural theory was done by Barkat in which subjects were asked to smell tertiary mixtures of odorants, previously determined to smell of pineapple, and compare the perception to the odorants in the mixture individually. The results indicated that while none of the components smelled of pineapple on their own, when combined together they produced a configural pineapple aroma (Barkat, Le Berre et al. 2012). However, an attempt to reproduce this effect using olfactometry was unsuccessful (Acree, Kurtz et al. 2014). Studies of odorant mixtures and how they are perceived may hint to the answer as well. For example, Berglund and Olsson showed that the intensity of a mixture is weaker than the sum of its individual parts, showing that while the elemental components are detectable in the mixture, the mixture is not simply a arithmetic combination of the parts (Berglund and Olsson 1993). This could be due to cross adaptation and mixture suppression, additional influences on the perception of odor mixtures that have been extensively studied (Kurtz, Lawless et al. 2010), (Laing and Wilcox 1983). By looking at neurological responses to odorants, it has been possible to study the plausibility of theses two theories, elemental and configural, and the possibility that both are true, by observing responses in different parts of the brain when subjects perceive odors and odor mixtures. Howard and Gottfried did this using fMRI univariate analysis to analyze the brains satiety based responses to peanut butter odor. The results showed evidence for elemental processing in that a subset of the components used in the odor mixture generated a decrease in satiety- related responses in the orbitofrontal cortex and amygdala. Furthermore, the results also showed evidence for configural processing in the posterior periform cortex by generating responses to the whole peanut butter odor that were not generated by any of the individual components of the odor (Howard and Gottfried, 2014). This is not the only study that shows that it might be that both of these theories are true, depending on the situation in which the organism is experiencing the mixture of odorants. For example, Laing and Livermore conducted a study on the spiny lobster in which it was shown that in some situations the lobster responded to a mixture of odorants as a unique entity, while in other cases, it responded to the individual elements of the mixture (Livermore, Hutson et al. 1997). Similar results were found years later, in 2011, when a study conducted on newborn rabbits examined the olfactory processing of odorants in mixtures, and found that the way the rabbits process mixtures of odorants is influenced by their past experiences (Sinding, Thomas-Danguin et al. 2011). Even more recently, a study found similar results in mice in that certain elements in a mixture of odorants can mask others dependent on the psychological responses (such as attraction and aversion) that they illicit (Saraiva, Kondoh et al. 2016).

1.2 Sensory Evaluation

Why do we eat? To acquire nutrients and to supply energy to our bodies, of course. But beyond this instinctual need to eat, humans have an emotional want to eat. We crave certain foods, we celebrate special occasions with meals, and we reward ourselves with delicious tastes and smells. Given that the perception and sensation derived from eating is such an important aspect of food, it is important to be able to quantify these perceptions. Sensory evaluation studies just that. Sensory evaluation uses a variety of protocols and equipment to measure human flavor responses to foods or beverages. This collected data can then be used to enhance and better understand the food industry as well as consumer demands.

The field of sensory testing and evaluation is vast, offering many ways of measuring many different aspects of sensorial perception. There are three types of test methods most prevalent in modern sensory evaluation, discriminative, descriptive, and affective. Discriminative testing is the simplest of these three categories, asking only whether a difference is present between two samples or products. Descriptive analysis focuses on the qualities of the product, asking for more detailed descriptions. This method is much more expensive and time consuming. Affective testing, however, quantifies degree of liking of a product. These three types of testing encapsulate the field of sensory evaluation (Lawless and Heymann 2010).

1.2.1 Thresholds

It was in 1824 that the idea of thresholds first surfaced. The philosopher Herbart determined that in order for any sensory perception to occur, there must be some critical level of stimulus present, and that under this level, no stimulus would be detected, this then is a threshold

(Gescheider 1985). This threshold is commonly referred to as the detection, or absolute, threshold- the smallest amount of stimulus that is perceivable. There are three additional types of thresholds that are also commonly recognized in sensory evaluation. The recognition threshold is the characteristics of a stimulus can be recognized nominally. The recognition threshold usually occurs at a slightly higher stimulus level than the detection threshold. The third type of threshold is the difference threshold. The difference threshold is the smallest amount of change in stimulus that a subject is able to recognize fifty percent of the time. The final type of threshold in sensory evaluation is the terminal threshold. This is the point above which the subject no longer perceives a change in stimulus. In other words their perception is at a saturation point such that they no longer perceive the stimulus as increasing (Lawless and Heymann 2010). This study will focus on the detection threshold for the threshold evaluations.

1.2.2 Psychophysics

Psychophysics is the study of the interaction between physiology and sensation. Psychophysics was from the observation by E.H. Weber that the amount of stimulus increase to generate a response increase was a constant ratio. This rule is now referred to as Weber's Law and is written as

$$\Delta I / I = k$$

ΔI is the increase in stimulus, I is the starting level of stimulus and the fraction is referred to as Weber's Fraction. Beyond this, G.T. Fechner added his own contribution to psychophysics. Fechner's Law examines the just noticeable difference, or JND. The JND is the smallest delta change in stimulus that will cause a change in response. Fechner discovered that the summation of JND's results in the construction of a psychophysical relationship between stimuli intensity and response level. This law is depicted as

$$S = k \log I$$

S is sensation intensity. I is physical stimulus intensity, as it is in Weber's Law. Fechner's law was modified 75 years later to become the power law

$$S = kI^n$$

Here, n is the characteristic exponent. This function is able to accommodate relationships that expand while the log function does not (Lawless and Heymann 2010), (Gescheider 1985).

1.3 Sniff Olfactometry

Sniff olfactometry is a means of collecting sensory data using a special olfactometer: a sniff olfactometer (SO). The design of the SO is such that a subject sits in from of the machine with their chin comfortably resting on a chin rest. The chin rest is positioned so that the subject's nose is directly about the sniff port, from which odors are delivered. Wihen the subject is sitting with their chin in the chin rest, they are 20 inches (50.8 cm) from a display screen.

When a test is run, the screen on the SO delivers visual cues to the subjects in a way that prompts them to inhale just before and during the time in which the puff of odorant is delivered. The timing and length of the puffs and regulated and randomized by the computer to ensure accurate and unbiased results. This procedure is regulated by PsychoPy™ (Peirce 2007). A representation of this procedure can be seen in figure 7b.

Subjects wear headphones to avoid any bias from auditaory cues, such as the sound of the actuators activating and to receive cues.

The Sniff Olfactometer can be loaded with up to three teflon bottles at a time. Teflon is used because it absorbes odorants poorly and very little monomer leaches into the solutions (Sacks, Gates et al. 2012). These bottles contain 15ml of solution, either of individual compoinds (threshold), pairs of compounds (binary anaylsis), tertiary mixtures of odorants (tertiary analysis), or boli of potato chips. The bottles are puffed via actuators in the SO, thereby delivering 75 milisecond-puffs of odorant out of the sniff port.

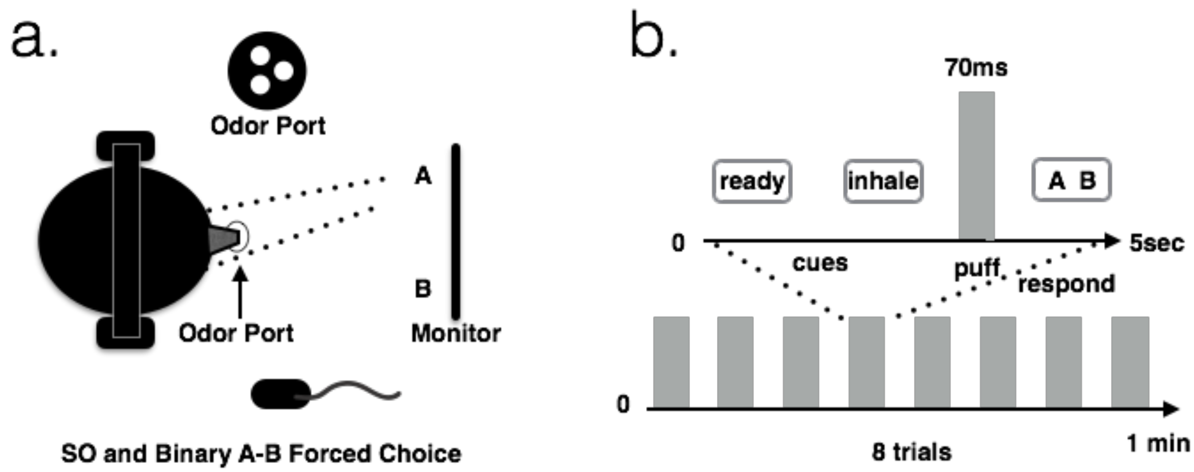


Figure 7: (a). Areal view of subject facing SO (b). representation of program and instructions on SO for threshold evaluation.

1.4 Potato Chip Industry

Potato Chips serve as an ideal model for this study for two reasons, their simplicity in aroma (as mentioned earlier), and their importance in the snack industry. According to a report done by the Institute of Food Technologists in 2016, potato chips can be found in three quarters of American homes. Additionally, the sale of salty snack foods has been steadily increasing, reaching $22 billion in 2015 in the U.S., an increase that is even more significant given that other snack and unhealthy foods have been in decline (IFT 2016). While potato chips remain in good standing in the eyes of the consumer, the increasing trend toward healthy snack foods creates a market toward which potato chip manufacturers must strive. For this reason research on potato chips is especially translatable in the current market. Additionally, according to a report done my Modor Intelligence, the potato chip market is projected to continue to grow by 4.3% between 2017 and 2022 when it will reach $40.3 billion. However, the report also points out the concentrated nature of the potato chip market due to the number of large companies controlling the majority share (Intelligence 2017). This competition between these large companies to win in the market is another reason for more and improved research on potato chips to generate innovation. This innovation could potentially come from responding to health related trends in the snack industry, or from a better understanding of quality and consistency in products to satisfy consumer demands, both of which are possible outcomes of this study.

1. Thesis Statement

The purpose of this thesis is to examine the possibility of recreating an odor image of a food product, in this case, potato chips. The research will attempt to generate the same olfactory response to a combination of three compounds, methional, methanethiol, and 2-ethyl-3,5-dimethyl pyrazine in a 10% ethanol solution, as actual potato chips. Furthermore this study will examine the variability between the olfactory perception in the thresholds to these odorants in different subjects, and the variability in the way different subjects perceive these odorants in binary and tertiary mixtures. It is also the purpose of this research to investigate the similarities in odor images between different subjects, in an attempt to determine whether different people experience different perceptions while exposed to the same olfactory stimuli.

3. Materials and Methods

3.6 Potato chips Acquisition

The potato chips used in this study were Lays Classic Potato Chips. Single proportion bags containing 1 ounce of chips were purchased in bulk. Once a bag was opened, the chips were used immediately to insure the chips would be at optimal freshness.

3.7 The SO

The Sniff Olfactometer was built by DATU inc. Geneva NY. with funds provided by San Ei Gen, F.F.I. Osaka Japan Label.

3.8 Subjects

Four human subjects were used in this study, 2 males and 2 females. The subjects were 22, 23, 27, and 29 years old. All were non-smokers and had no history of olfactory defects. All were students or employees of Cornell

University department of Food Science. None had prior experience with olfactory testing.

3.9 Chemicals

Methional CAS number 3268-49-3 (>97%) (MAL), methanethiol (MOL) CAS number 74-93-1 (>98%), and 2-ethyl-3,5-dimethylpyrazine CAS number 27043-05-6 (>95%) (2E3,5DP)were from Sigma Aldrich (St Louis, USA). Solutions were made in distilled water containing 10% v/v ethanol (food grade). Test solutions ranged from 1 ppm to 200 ppm for MAL, 10ppm to 1000ppm MOL and 50ppb to 300ppb 2E3,5DP.

3.5 Threshold Determination

The threshold for each subject and for each odorant was determined by using a 2 alternative forced choice test by testing for detection of different concentrations of odorants diluted in 10% EtOH against a blank containing only 10% EtOH using the sniff olfactometer.

3.5.1 Materials for Threshold Determination

To determine the threshold for an each odorant, the odorant was diluted to different concentrations in 10% ethanol and 50 milliliters of the diluted odorant was added to a 250 mL Teflon bottle. A blank was prepared by adding 50 milliliters of 10% ethanol to a Teflon bottle. The samples were made 48 hours before the study and stored in brown glass bottles. The samples were transferred to the Teflon bottles within 24 hours of the trial.

Position Number	Right Bottle	Center Bottle	Left Bottle
1	High Concentration	Blank	Low Concentration
2	Low Concentration	High Concentration	Blank
3	Blank	Low Concentration	High Concentration

Table 1: Bottle positioning in SO for threshold evaluation

3.5.2 Method for Determining Threshold

Two Teflon bottles, each containing different concentrations of the same odorant were then installed in the sniff olfactometer. The positioning of the bottles can be see in table 1. For example, for position 1 the bottle containing the higher concentration was placed in the right position while the bottle containing the lower concentration was placed in the left position. The blank was a Teflon bottle containing 50 milliliters of 10% ethanol, and was placed in the center for bottle positioning 1. The bottles start in position 1 and changing to position 2 and 3 after puff 6 and 12 respectively when a prompt appears asking the subject to tell the technician to change the bottle position. This acts to increase randomization and decrease bias. Once the bottles were loaded into position, the block of bottles was slid into the correct place and tightened. With the bottles in position, the subject then sat in front of the SO and adjusted the chair so that their chin rested comfortable on the chin rest, and their nostrils were positioned directly above the sniff port. With the subject comfortably in position, the SO program was started. The subject first received a training prompt in which they receive two puffs. They are then prompted to say which puff was stronger. This is then repeated 18 times. At the completion of the 18 puffs, the program thanked the subject and saves the data to an excel sheet. The technician then started the program over again with two new concentrations, as necessary. This was repeated until the data reflected a concentration at which the subject could detect the odor at every puff of the bottle containing that odorant, and a concentration at which the subject cannot detect the odor when the bottle containing that odorant is puffed. This is represented by points at which they correctly identify the stronger of 2 puffs, indicating that the subject is above threshold, and a point at which the subject incorrectly chooses the stronger puff, indicating that they are below threshold and the ethanol therefore smells stronger than the odorant. This resulting data was then analyzed using a Mathematica (Wolfram Research). An algorithm (Appendix) read the data from the excel file (Appendix) into a mathematica file where it was fit to a logit function and the probability of a response was plotted against the log of the concentration in the solution. The definition of the threshold was the concentration in the solution that produced a 50:50 response probability. No Abbott correction was applied since the choice was between two signals (e.g. EtOH odor and the odorant +EtOH odor). The subject was not asked to choose between the detection of an odorant (signal + noise) and no detectable signal (noise).

3.6Analysis of Binary Mixtures

Mixtures of two odorants were analyzed to determine the point at which the subject detected each of the two odorants equally. This point will be referred to as the equal odds ratio, or (EOR).

3.6.1 Materials for Binary Mixture Comparisons

To examine the way in which two odorants behave in a mixture, multiple solutions containing different levels of the same two odorants were prepared. Mixtures were prepared at varying ratios of the two odorants being examined. The solutions were prepared more than 24 hours before analysis and were kept in glass bottles, and then 50 milliliters of the combined solution was transferred to Teflon bottles at the time of study.

3.6.2 Method for Binary Mixture Comparisons

When analyzing binary mixtures of odorants, three bottles, each containing different ratios of the two odorants, are placed in the SO. The location of the bottle containing each ratio is marked. Once the bottles were loaded into the SO, the subject sat in front of the SO with their chin resting comfortably on the chin rest and the mixture comparison program was run. The experiment followed an alternative forced choice protocol (Lawless). The program began with a training exercise that prompted the subject to inhale a single puff and decide which of the two odorants they detected. The puffs were generated randomly from the SO to decrease the chance of bias. The subject was presented with 24 puffs, 8 from each bottle and ratio. Upon completion of the 24 puffs, the program ended, and new bottles containing new ratios were added to the SO and the program was run again. This was repeated until the desired range of data had been collected. The data was then analyzed with Mathematica, and the EOR for the two odorants was determined. This was repeated with the three possible pairwise combinations for the three odorants.

3.7 Analysis of Tertiary Mixtures

Upon completion of the analysis of odorants in binary mixtures, the perception of odorants in tertiary odorants was analyzed. The level at which the subjects detected each of the tree odorants equally was the tertiary odds ratio, or TOR.

3.7.1 Materials for Tertiary Comparisons

Tertiary solutions were prepared using odorants diluted in 10% ethanol. A range of solutions was created such that the odorants were present at different ratios relative to one another. The solutions were assigned numbers and labeled accordingly. The solutions were prepared 48 hours prior to analysis and were stored in glass bottles. 50 mL of the solutions was then added to Teflon bottles up to 24 hours before analysis.

3.7.2 Method for Tertiary Comparison

Tertiary solutions of the odorants in Teflon bottles were added to the SO 3 at a time. The location, left center or right, of each bottle was noted. The bottles were then slid into the SO and locked into place. The subject sat facing the SO with their chin resting comfortably on the chin rest. The trio analysis program was then run using a tertiary forced choice of labels for each trial. The program began with a training exercise in which a single bottle was puffed, and the subject was asked to decide if they smelled potato, toast, or cabbage. After the training exercise, the subject received 36 additional puffs from the three bottles in a random order and was prompted to choose one of the three descriptors for each puff. Upon completion, the program was closed and the probabilities in the excel file was compared for each word choice. More bottles containing different tertiary ratios were analyzed in this way until a solution was found to which the subject gave approximately equal responses of each descriptor (30:30:30). This was defined as the TOR.

3.8Comparison to Potato Chip

After determining the threshold for each odorant, the binary EOR for each pair of odorants, and the TOR for the tertiary mixture of odorants, tertiary solutions were compared to actual potato chips. This was done to determine whether a combination of just three odorants could simulate the same perception as an actual food product, or generate an “odor image”, at the Configural Odds Ratio, or COR.

3.8.1 Materials for Potato Chip Comparison

Tertiary solutions for analysis were prepared following the same protocol as for the analysis of the TOR. Solutions were chosen from the tertiary analysis that represented a wide range of responses from the subject, including the solution that yielded the TOR. These solutions were prepared, stored in brown glass bottles, and transferred to Teflon bottles up to 24 hours before analysis.

A bolus of potato chip was prepared by crushing one gram of Lays Original potato chips, approximately the same amount as in a typical bite of potato chips and mixing it in 49mL of EtOH. This bolus was then added to a Teflon bottle and labeled potato chip. This was the control. The bolus was prepared immediately before the trial in order to simulate the same sensation as eating a fresh potato chip.

3.8.2 Method for Potato Chip Comparison

The program used to compare tertiary solutions to the bolus of potato chips was the same program that was used to analyze binary mixtures of odorants. However, in this comparison, the subject was asked to choose between "Potato Chip" and "Not Potato Chip" in the forced choice test. Three Teflon bottles were placed in the SO, two containing tertiary solutions of odorants, and one containing the actual bolus of potato chips. The block of bottles was slid into place and locked in. The subject received a single puff from a bottle and was prompted to state if they thought it was potato chips or not. The program gave a training exercise followed by 24 puffs from random bottles. Upon completion, the data was exported to excel, and the technician continues the process by switching the Teflon bottles containing tertiary solutions with bottles containing different tertiary ratios. This was repeated until a range of solutions had been compared to the potato chips, and a solution was found that simulated the perception of the potato chip. This solution represented the configural odds ratio (COR), a formulation that generated the odor image of the potato chip.

4. Results

4.1 Threshold Results

4.1.1 Pyrazine Thresholds

The subjects were found to have varying threshold for Pyrazine. The range of thresholds was from .116ppb to 22.1ppb, as show in table 2. The psychometric curves for the pyrazine threshold determination for subjects A, B, C, D can be found in figure 8, parts A, B, C, and D, respectively.

4.1.2 Methional Thresholds

The subjects were found to have extreme variations in threshold for Methional. The range of thresholds was from .836 ppb to 180 ppb, as show in table 2. The psychometric curves for the Methional threshold determination for subjects A, B, C, D can be found in figures 9, parts A, B, C, and D, respectively.

4.1.3 Methanethiol Thresholds

The subjects were found to have significant variations in threshold for methanethiol. The range of thresholds was from .004ppb to 92.1ppb, as show in table 2. The psychometric curves for the methanethiol threshold determination for subjects A, B, C, D can be found in figures 10, parts A, B, C, and D, respectively.

Subject	Pyrazine	Methional	Methanethiol
A	0.836	0.116	0.004
B	0.202	4.24	92.1
C	21.5	180	41.1
D	22.1	17	.041

Table 2: Summary of threshold results for each odorant for each subject

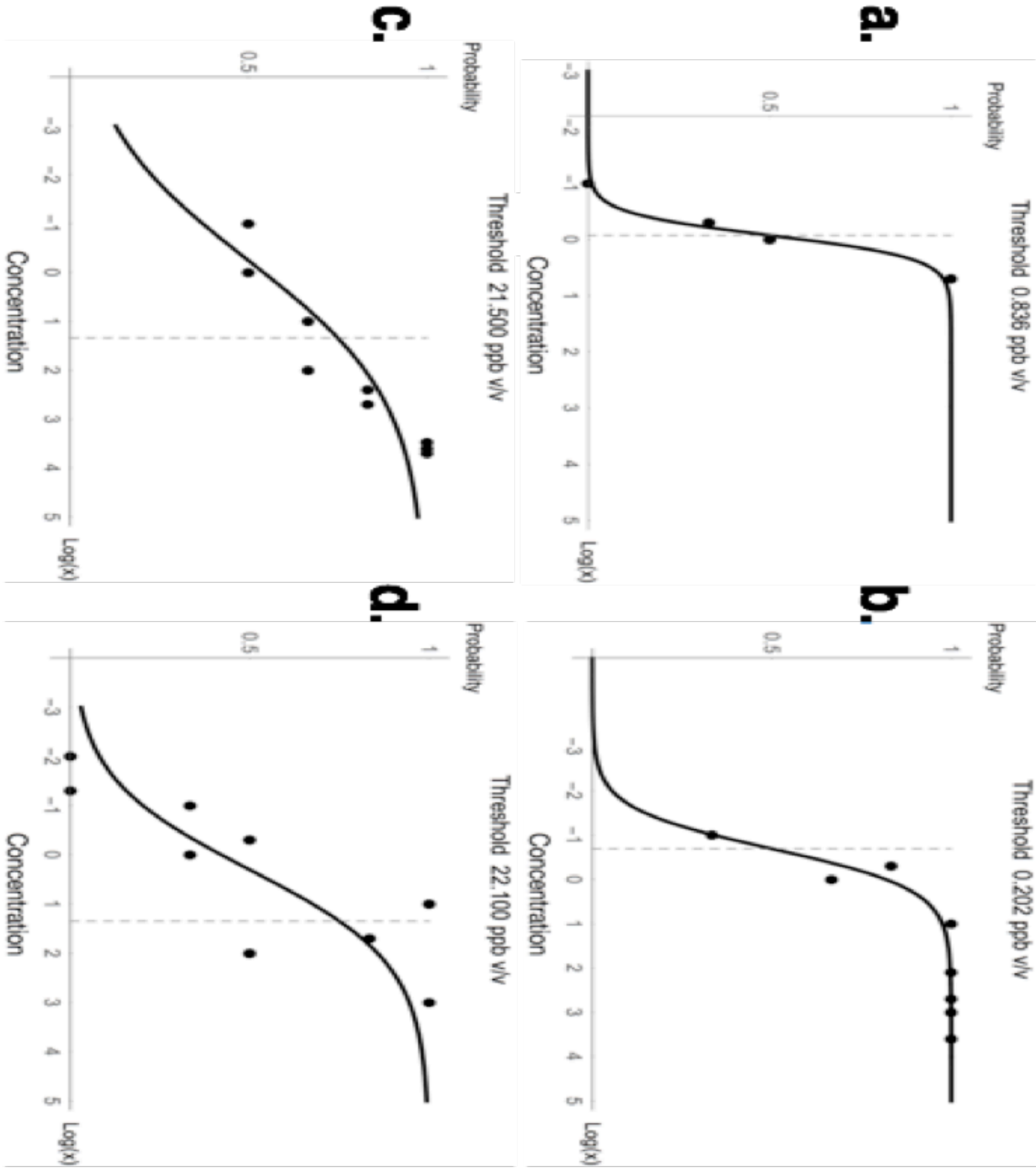


Figure 8: Pyrazine threshold psychometric functions for subject A (a.), subject B (b.), subject C (c.), and subject D (d.)

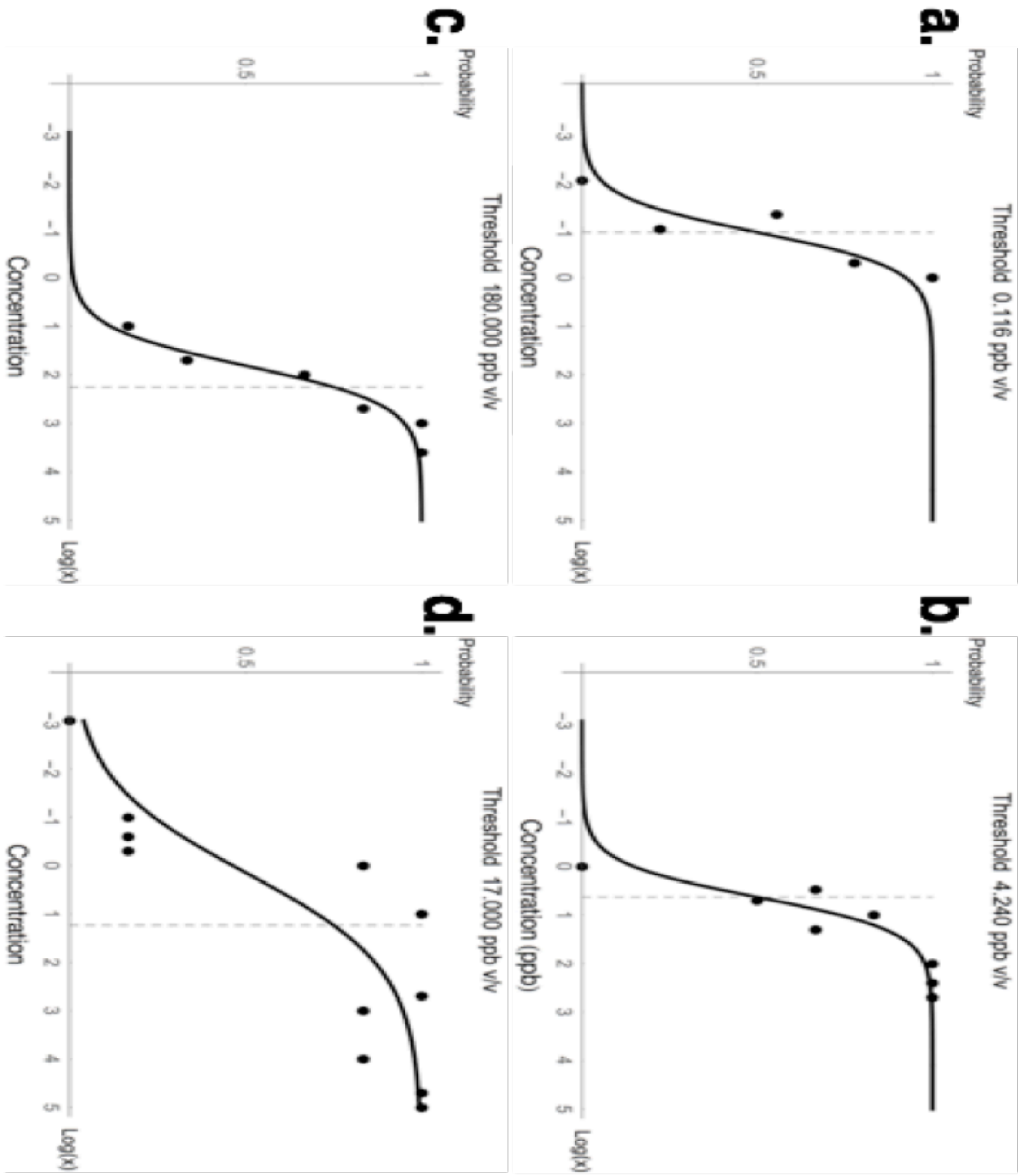


Figure 9: Methional threshold psychometric functions for subject A (a.), subject B (b.), subject C (c.), and subject D (d.)

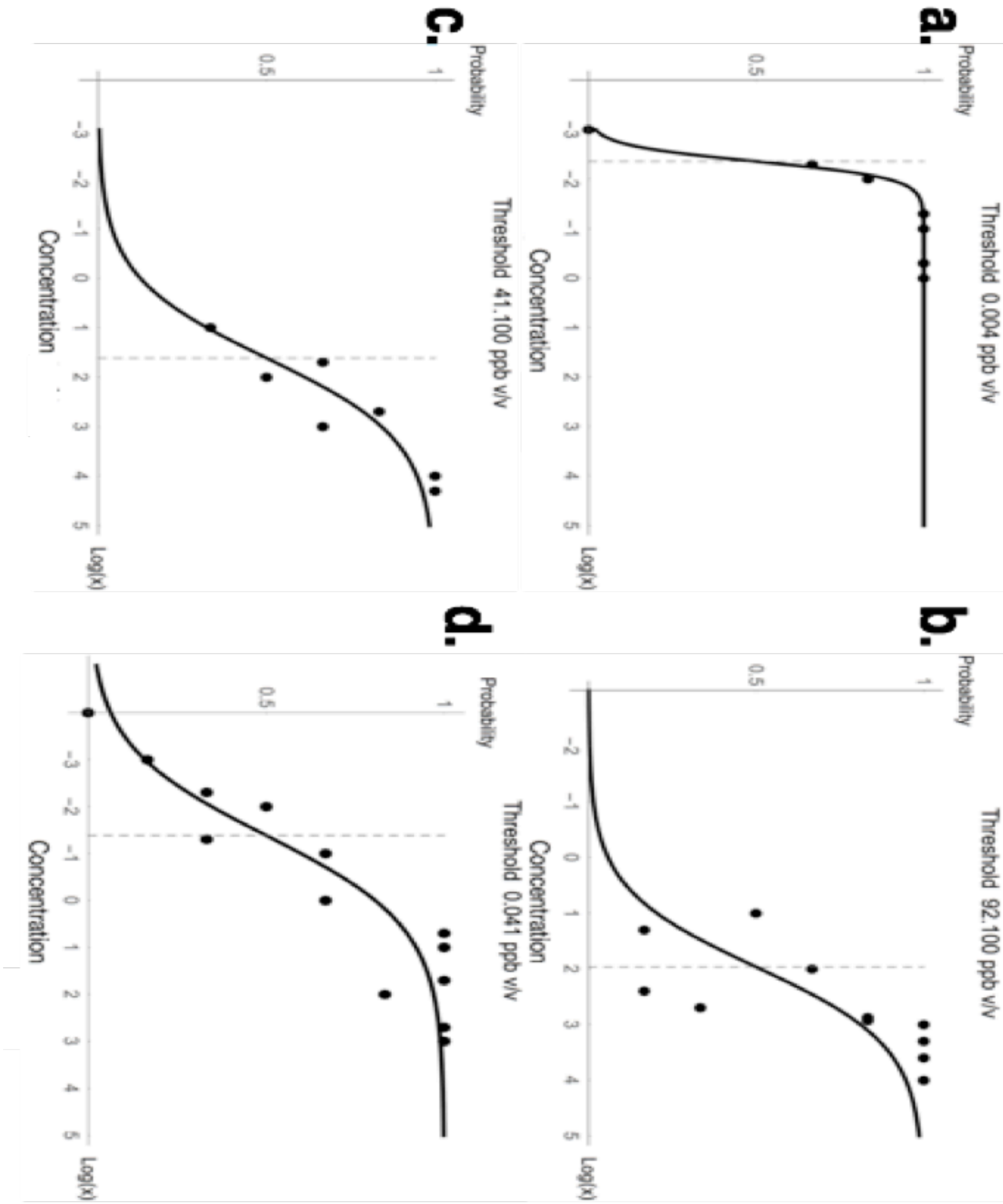


Figure 10: Methanethiol threshold psychometric functions for subject A (a.), subject B (b.), subject C (c.), and subject D (d.)

4.2 Binary Results

4.2.1 Mixture 1 Methional : Methanethiol

The equal odds ratio (EOR) for Methional to Methanethiol (mixture 1) was defined as the concentrations at which each compound can be equally detected in a mixture. The EOR's for this mixture varied from ratios of .075 to 15.3. The results for the binary EOR's can be found in table 3. The curves for the binary comparisons between methional and methanethiol for subject A, B, C, D can be found in figures 11, parts A, B, C, and D, respectively.

4.2.2 Mixture 2 Pyrazine : Methanethiol

The equal odds ratio (EOR) for to Pyrazine to Methanethiol (mixture 2) was defined as the concentrations at which each compound can be equally detected in a mixture. The EOR's for this mixture varied from ratios of .002 to 117. The results for the binary EOR's can be found in table 3. The curves for the binary comparisons between methanethiol and pyrazine for subject A, B, C, D can be found in figures 12 parts A, B, C, and D, respectively.

4.2.3 Mixture 3 Pyrazine : Methional

The equal odds ratio (EOR) for Pyrazine to Methional (mixture 1) was defined as the concentrations at which each compound can be equally

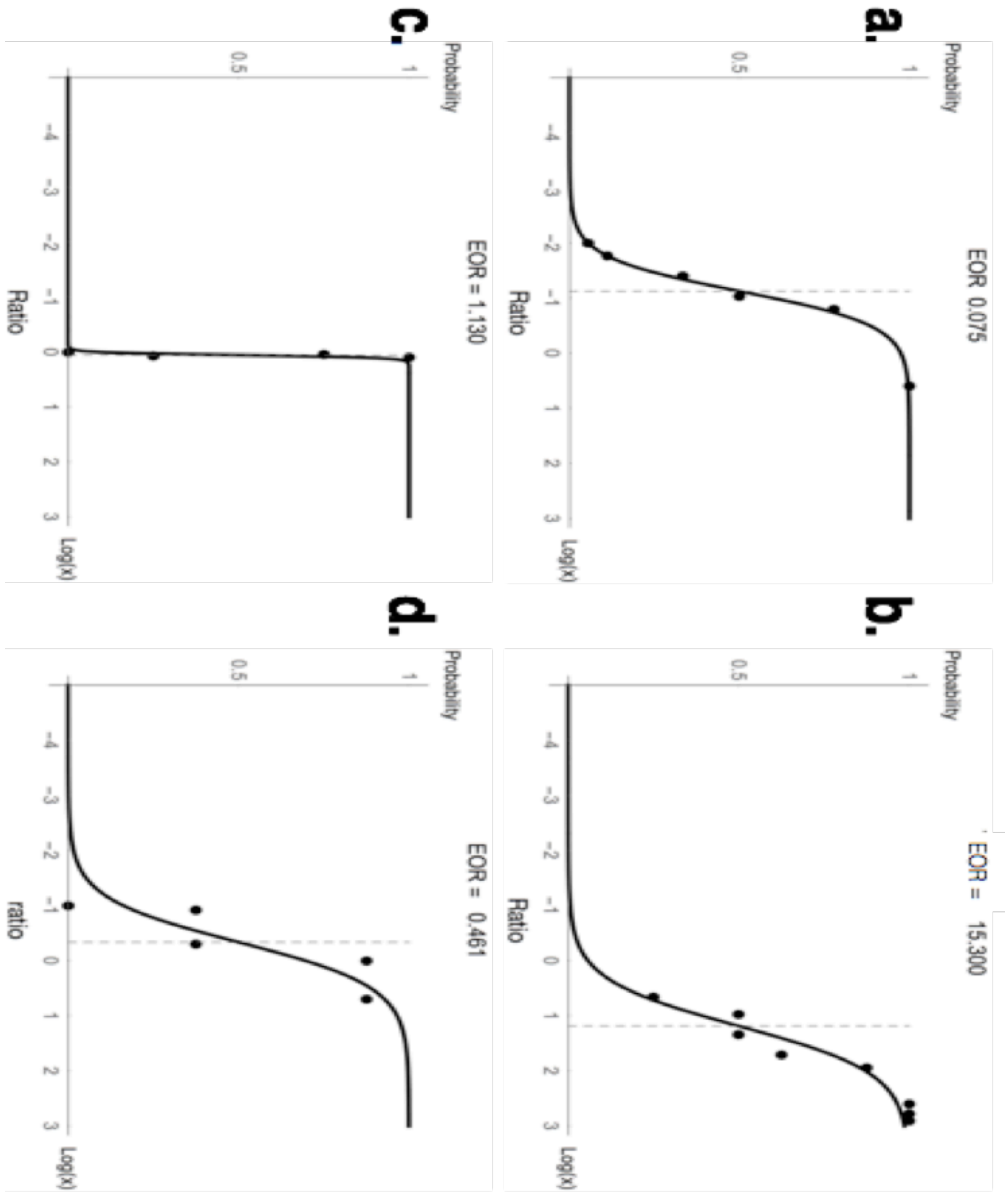


Figure 11: Binary Results for Mixture 1 (Methional:Methanethiol) for subject A (a.), subject B (b.), subject C (c.), and subject D (d.)

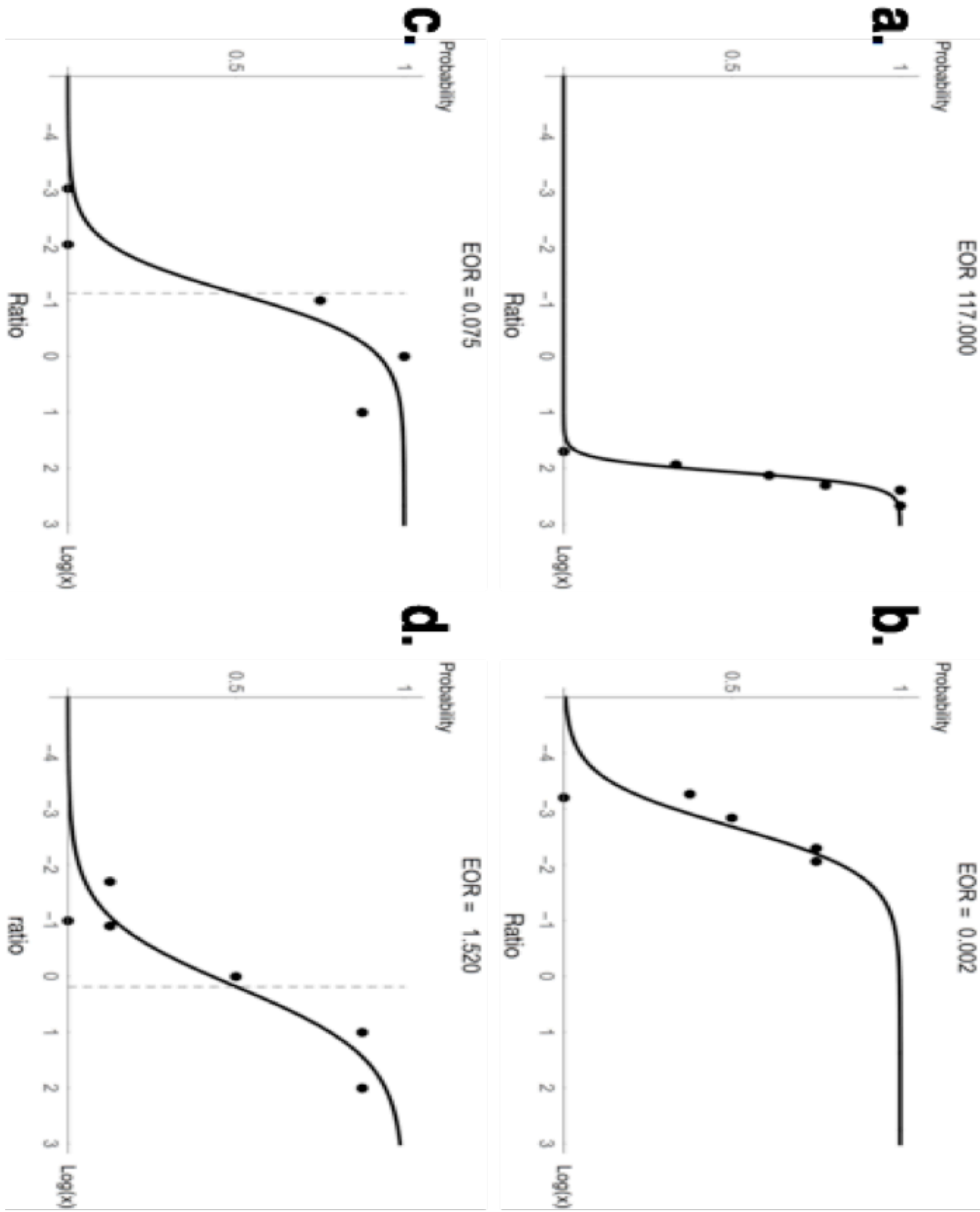


Figure 12: Binary Results for Mixture 2 (Pyrazine:Methanethiol) for subject A (a.), subject B (b.), subject C (c.), and subject D (d.)

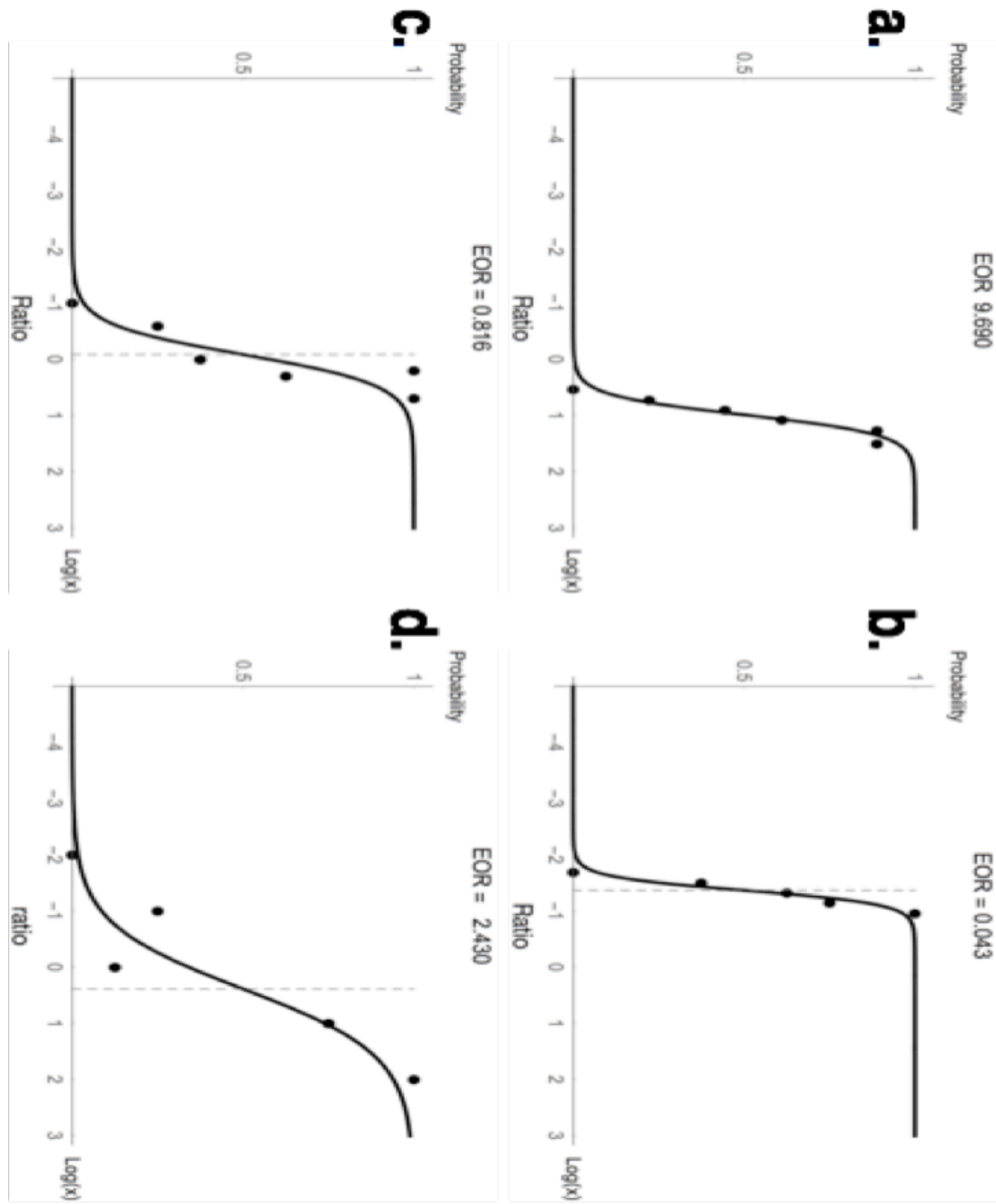


Figure 13: Binary Results for Mixture 3 (Pyrazine:Methional) for subject A (a.), subject B (b.), subject C (c.), and subject D (d.)

detected in a mixture. The EOR's for this mixture varied from ratios of .043 to 9.69. The results for the binary EOR's can be found in table 3. The curves for the binary comparisons between methional and pyrazine for subject A, B, C, D can be found in figure 13 parts A, B, C, and D, respectively.

	Mixture1	Mixture2	Mixture3
Subject			
A	0.075	117	9.69
B	15.3	0.002	0.043
C	1.13	0.075	0.816
D	0.461	1.52	2.43

Table 3: Equal Odds Ratios for each subject and for each mixture;

Mixture 1- Methanethiol:Methional, Mixture 2- Pyrazine: Methanethiol,

4.3 Tertiary Results

The Tertiary Odds Ratio, or TOR, was defined as the solution containing all three compounds to which the subjects responded approximately equally with the three responses. i.e. they said the solution smelled like potato approximately 33% of the time, toast approximately 33% of the time, and cabbage approximately 33% of the time. The concentrations of each compound in each subject's TOR solution can be found in table 4. For subject A, the methional was most potent in the TOR, as it was 23 times stronger than the pyrazine, which was 89 times more potent than the methanethiol. For subject B, the methanethiol was most potent in the TOR, as it was 3 times stronger than the methional, which was 31 times more potent than the pyrazine. For subject C, the methanethiol was also most potent in the TOR, however it was only 1.2 times stronger than the pyrazine, which was only 3 times more potent than the methional. Finally, for subject 4 the concentrations of the pyrazine and methional were equal, and were exactly double the concentration of the methanethiol in the solution. This is shown in figure 14.

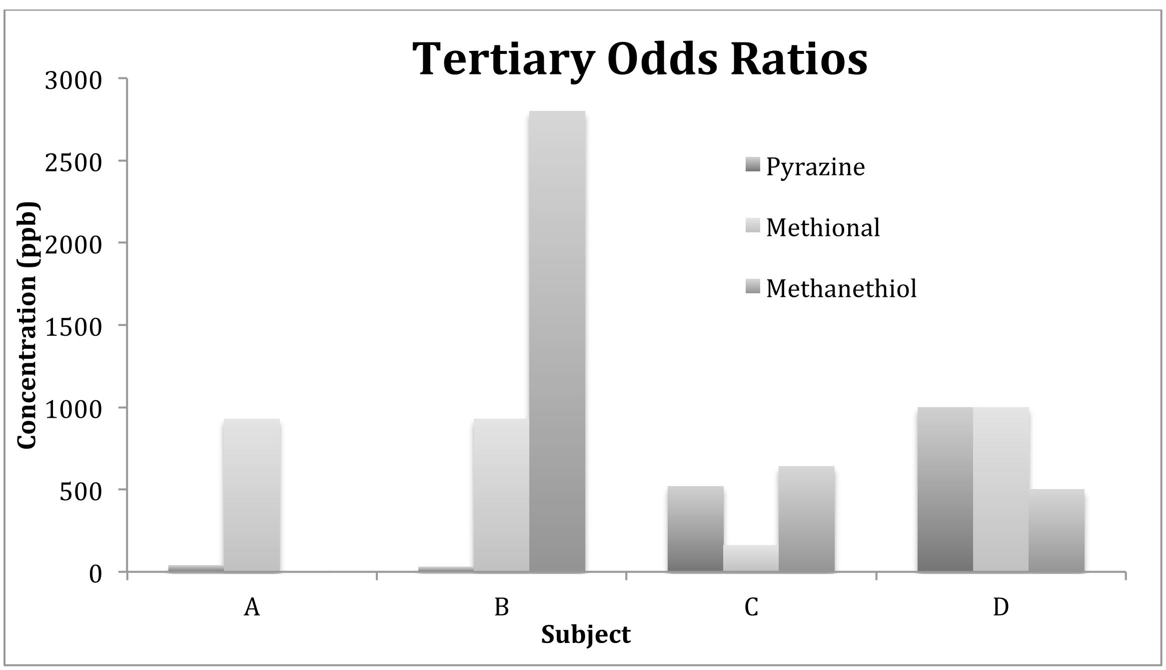


Figure 14: Concentrations of pyrazine, methional, and methanethiol in solution determined to be TOR for each subject

	TERTIARY ODDS RATIO		
Subject	Pyrazine	Methional	Methanethiol
A	40	930	0.448
B	30	930	2800
C	520	160	640
D	1000	1000	500

Table 4: Concentrations of each odorant in the tertiary odds ratio solution(solution that smelled equally of potato, toast, and cabbage

4.4 Configural Results

The configural odds ratio, or COR, was defined as the combination of concentrations at which the subject could not differentiate between a bolus of potato chips and the solution. For three of the four subjects this combination was the same. Subject C had a significantly different COR than subjects A, B, and D, as seen in table 5 and again in figure 15. Furthermore,

Subject	Pyrazine	Methional	Methanethiol
A	40	930	2800
B	40	930	2800
C	400	400	80
D	40	930	2800

Table 5: Concentrations of each odorant in the configural odds ratio solution (solution determined to smell like potato chips for that subject)

the predicted responses to the individual components present

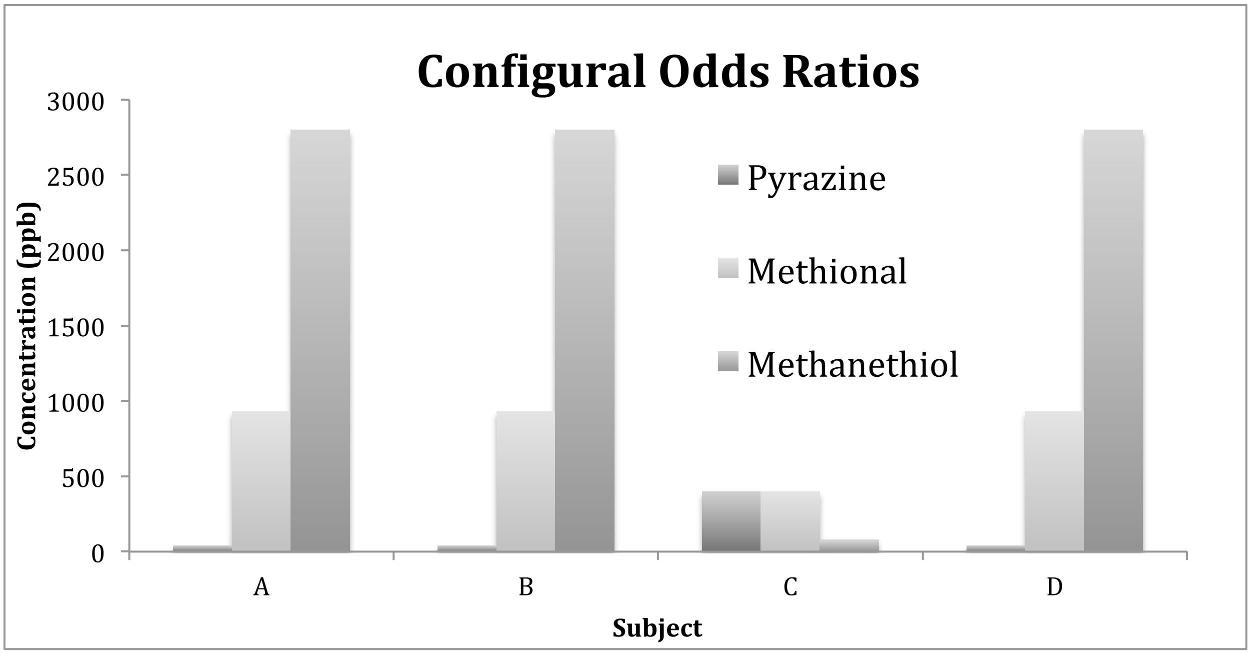
in the configural odds ratio solution for each subject that shared the same COR were different for each subject, as shown in figure 15.

5. Discussion

The results of this study indicate that subjects have varying thresholds to different compounds. This variation in level of detection between subjects results also in differences in the equal odds ratios between compounds, and in the tertiary odds ratios between mixtures of all three compounds. However, while the thresholds and odds ratio has great variability between subjects, the majority of subjects tested determined the same combination of components to be “potato chip”. Furthermore, the analysis of that same COR mixture which subjects A, B, and D all described as potato chips, reveals that while the subjects give the same name to the solution, they are all actually experiencing very different things. This result shows that it is our experiences that guide our nominal labeling to the odors around us.

6. Conclusions

The most notable conclusion from this research is that our while the physical stimulus in the world around us is the same for each of us, we are all living in our own olfactory worlds. There is great variability in different people’s thresholds for detecting odorants, and great variability in the way those



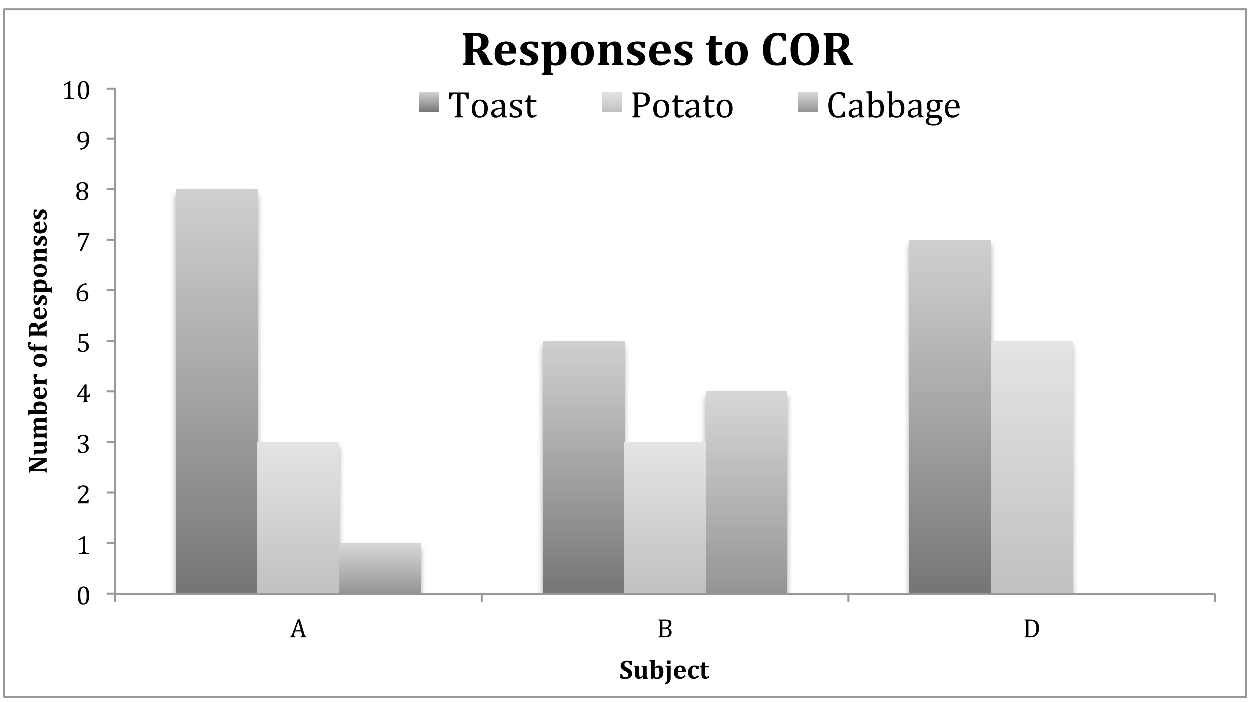


Figure 15: Concentrations found in solutions determined to be "potato chip" by each subject (top) and responses of subjects A, B, and D to the solution determined to be "potato chip"

subjects perceive odorants in mixtures, both binary, tertiary, and beyond. Due to these different thresholds for different odorants, we perceive mixtures of odorants, and therefore foods and drinks, very differently. However, due to our associative learning, and years of calling chips chips, we all identify the same stimulus to be potato chips. Therefore, when we are sitting around a bowl of chips snacking with friends, those chips are completely different for each of us, yet no one denies that they are potato chips.

7. Future Direction

First and foremost of future work should be to increase the number of subjects used in this study. This would better illuminate whether subject C was in fact an outlier. Furthermore, it has been mentioned already in this report that potato chips provide a simple model for this study. It is therefore only natural to use this study as a platform for different and more complex systems, such as sauvignon blanc wine. Additionally it is an obvious next step to examine the translational impacts of this research. For example, many subjects mentioned during testing that some mixtures smelled “saltier” than others. Being that salt is a mineral, it has no smell, and this perception must therefore be coming from associative learning. It can be speculated then that by manipulating the odor image of sodium reduced chips, it could be possible to create the illusion of salt without the negative health effects. This of course needs much more investigation, but could be an exciting path to embark on as a result of this research. The difference in perception of products between subjects could also explain differences in preferences between consumers, but again this must be further investigated. Finally, there are many things about olfaction that we do not yet understand, and we must continue to study this exciting field until these questions are answered.

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